

Substorms and Magnetic Storms From the Satellite Charging Perspective

28 February 2001

Prepared by

J. F. FENNELL, H. C. KOONS, J. L. ROEDER, and J. B. BLAKE
Space Science Applications Laboratory
Laboratory Operations

Prepared for


SPACE AND MISSILE SYSTEMS CENTER
AIR FORCE MATERIEL COMMAND
2430 E. El Segundo Boulevard
Los Angeles Air Force Base, CA 90245

Engineering and Technology Group

This report was submitted by The Aerospace Corporation, El Segundo, CA 90245-4691, under Contract No. F04701-00-C-0009 with the Space and Missile Systems Center, 2430 E. El Segundo Blvd., Los Angeles Air Force Base, CA 90245. It was reviewed and approved for The Aerospace Corporation by L. M. Friesen, Acting, Principal Director, Space Science Applications Laboratory. Michael Zambrana was the project officer for the Mission-Oriented Investigation and Experimentation (MOIE) program.

This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.


Michael Zambrana
SMC/AXE

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE 28 February 2001		3. REPORT TYPE AND DATES COVERED
4. TITLE AND SUBTITLE Substorms and Magnetic Storms From the Satellite Charging Perspective			5. FUNDING NUMBERS F04701-00-C-0009	
6. AUTHOR(S) J. F. Fennell, H. C. Koons, J. L. Roeder, and J. B. Blake				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) The Aerospace Corporation Laboratory Operations El Segundo, CA 90245-4691			8. PERFORMING ORGANIZATION REPORT NUMBER TR-2000(8570)-2	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Space and Missile Systems Center Air Force Materiel Command 2430 E. El Segundo Boulevard Los Angeles Air Force Base, CA 90245			10. SPONSORING/MONITORING AGENCY REPORT NUMBER SMC-TR-01-10	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) Substorms and magnetic storms generate significant space weather effects in the inner magnetosphere. They change the dose rates experienced by satellites in many orbits and are directly linked to the occurrence of satellite charging. Substorms inject hot plasma into the nightside magnetosphere. The drifting electron component of this hot plasma can charge the surfaces of the satellites, leading to electrostatic discharges and associated satellite anomalies and sometimes failures. These occur in regions that are consistent with the expected motions of the substorm injected particles. The high-energy electron enhancements associated with many magnetic storms can be sufficient to cause charging of satellite elements even behind significant shielding. Not all magnetic storms result in flux enhancements sufficient to cause such internal charging. Because the induced voltages from the internal charging are usually not directly measured, the anomalies they cause are more difficult to link to the space environment and the magnetic storm related space weather. However, the anomaly statistics were sufficient to show linkage in a few cases. Data from different satellites will be used to show the measurement of surface charging from different regions of space and link the charging to electrostatic discharges and anomalies. Similarly, we will show the magnetic storm-related variability of the high-energy electron fluxes and provide a look at some of the evidence that these penetrating fluxes can lead to spacecraft anomalies.				
14. SUBJECT TERMS Spacecraft charging, Magnetic storm effects, Substorm effects, Substorms			15. NUMBER OF PAGES 24	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT	

Acknowledgement

This work was supported by the Aerospace Corp. MOIE program under U. S. Air Force contract F04701-93-C-0094.

Contents

1. Introduction.....	1
2. Satellite Charging	3
2.1 Satellite Surface Charging.....	3
2.1.1 Surface Charging Environment.....	4
2.1.2 Equatorial Satellite Surface Charging.....	5
2.1.3 High-Altitude Off-Equator Satellite Surface Charging.....	9
2.1.4 Complexities of Surface Charging	12
2.2 Internal Charging.....	13
2.2.1 Internal Charging Observations.....	14
2.2.2 Causes of Internal Charging—Magnetic Storms.....	15
2.2.3 Causes of Internal Charging—Energetic Electron Variability.....	15
2.2.4 Relation between Internal Charging ESD and Penetrating Electron Fluxes	15
2.2.5 Internal Charging Specifications.....	17
3. Discussion.....	21
References.....	23

Figures

1. Cartoon showing the currents that flow to/from an object in the space plasma.	4
2. Substorm plasma injection.....	5
3. Local time dependence of anomalies observed on geosynchronous satellites.....	6
4. SCATHA plasma spectrogram showing evidence of satellite charging in both electrons (top panel) and ions (bottom panel).	6
5. Example of substorm-related charging near midnight.....	7

6. Location of surface charging as determined by SCATHA.....	8
7. Anomaly occurrence versus Kp.....	8
8. HEO anomalies mapped to magnetic equator. Symbols indicate Kp value.....	10
9. Plasma electrons and ions from the Aerospace HEO 95-034.....	10
10. Occurrence of >100 V satellite frame potentials in HEO/Molniya orbit.....	11
11. Comparison of a “Worst-Case” plasma electron spectrum and an average electron spectrum. Note the similarities.	12
12. Local time distribution of surface ESD on SCATHA.	13
13. Local time distribution of internal ESD on SCATHA.....	14
14. Variation in the energetic electron fluxes at geosynchronous orbit during a period of successive high-speed solar wind streams in 1994.	16
15. Comparison of SCATHA anomalies with energetic electron fluxes.	16
16. Fractional reduction in electron flux by aluminum shielding.....	17
17. Examples of worst-case 10-hour-average electron spectra for three different orbits.	18
18. Shielding required to protect HEO and GEO satellites from the worst-case average electron spectra.	18

Tables

1. Distribution of Records by Anomaly Diagnosis.....	3
--	---

1. Introduction

The study of magnetic storms and substorms has been a focus of the scientific community for a long time. Much effort has gone into trying to determine the cause and effect relationships for storms and substorms and the resultant changes in the magnetosphere observed by satellites and ground observatories. The space weather community uses the results of these studies in their attempts to predict the occurrence of the storm and substorm events and to try to gauge the seriousness of their consequences. Much of the work in the space weather community is focused on the development of predictive models. The driving force behind this effort is the conviction that the storms and substorms cause serious problems for technology that we rely on for many services. It is also driven by the assumption that knowledge of where and when such environmental events will occur can be used to reduce or manage the problems they cause. In this report, we present the results of different studies of phenomena that can have deleterious effects on space assets in the inner magnetosphere. In particular, the focus of this report is to identify satellite charging as a threat to spacecraft and to show the link between such charging, magnetic storms, and magnetospheric substorms.

2. Satellite Charging

Satellite charging is a simple concept, and its analog is easily experienced by anyone who shuffles his or her feet across a rug on a dry day. The charge transferred by friction causes the person to become charged relative to their surroundings. The result can be a surprising or painful electric discharge from the person to a nearby object. The same kind of discharge, called an electrostatic discharge or ESD, can occur on a satellite when its surfaces or interior elements build up extreme levels of excess charge relative to the space plasma or to neighboring satellite components. The ESD releases a surge of energy that can be coupled into electronics causing upsets and damage. The optical emissions from the discharges can cause spurious responses from optical systems. The electromagnetic noise from discharge can be coupled into receivers and is a nuisance to the system's users.

The problems caused by charging on satellites have been compared to other environmental effects in a recent Aerospace Corporation study.¹ Some of the main results of this study are summarized in Table 1, which indicates that satellite charging is responsible for more than half (161 out of 198) of the environment-related anomalies. The study results also showed (see Table 2 of Ref. 1) that ESD caused about 50% of the lost or terminated missions associated with environmental effects. Thus, the issue of satellite charging is very serious from the perspective of the threat it poses for satellites with orbits in the inner magnetosphere. Therefore, it is important to understand where and why satellites charge and how the charging is related to magnetospheric and solar-terrestrial processes.

2.1 Satellite Surface Charging

The space plasma impinging on a satellite carries a current. The low-energy component of that plasma does not penetrate into the satellite materials but resides near the surface. The incident plasma particles and the solar UV also interact with the satellite materials to generate secondary electrons. The surface materials of a satellite will take on a charge such that the net current between the surface and the plasma is zero under quiescent conditions. This is presented schematically in Figure 1 where the charges flowing to and from a body immersed in the space plasma are shown. The "satellite," in this case, is an insulator. Charge cannot move across the surface or through the volume from the sunlit side to the dark side or vice versa. The surfaces charge until the net current is zero at each element of surface area. The result is that the surface voltage is usually not zero. The sunlit areas are

Table 1. Distribution of Records by Anomaly Diagnosis

Diagnosis	Number of Records
ESD—Internal Charging	74
ESD—Surface Charging	59
ESD—Uncategorized	28
Single-Event Effects	85
Damage	16
Micrometeoroid/Debris Impace	10
Miscellaneous	26

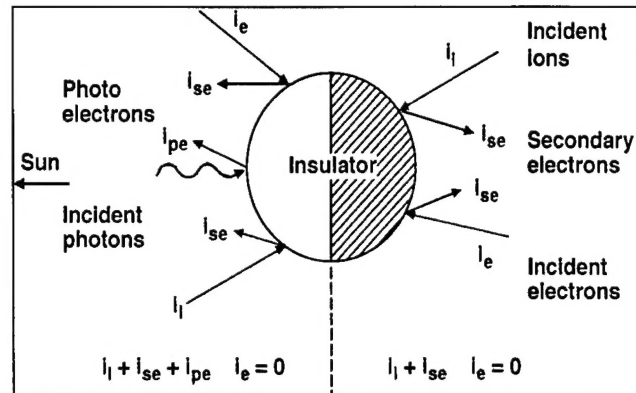


Figure 1. Cartoon showing the currents that flow to/from an object in the space plasma.

usually slightly positive and the shadowed areas are usually negative relative to the plasma at “infinity.”

If the surface were a conductor, the net current to the surface as a whole would be zero and the potential of the surface would be uniform and either positive or negative relative to the plasma. The plasma electrons are usually the dominant source of initial plasma current to a body because of their higher speed compared to that for ions of similar energy. The photo and secondary electron currents from a body are usually higher than the plasma electron current to the body, during average conditions. If the body is in a “hot” plasma (electron average energy \geq keV), its shadowed regions will generally charge negative to significant potentials, sometimes several kilovolts. If the “hot” plasma is also relatively dense, then even the sunlit regions of the body can charge to significant levels.

Because the secondary and photoelectron currents are different for every material in the same environment, a real satellite, constructed from many different conductive and nonconductive materials, will have a range of surface potentials. The differences in potential between adjacent materials, such as thermal blankets and metallic structure, can lead to local electrical stress. This can result in vacuum arcs. It is also possible for a surface material to discharge into space, a so-called “blow-off” discharge or to structure ground. The resulting ESD currents can electromagnetically couple into electronic circuits and subsystems, causing mischief or damage as noted above.

2.1.1 Surface Charging Environment

The plasma electrons are the primary source of current that causes high levels of charging. These electrons usually have energies of a few hundred to a several thousand eV, but generally less than 50 keV. Above 25 to 30 keV, the electrons start to penetrate thin materials such as monolayer thermal blankets or paints and start to generate internal charging of thick materials or the underlying structure. In the regions where the magnetospheric plasma is very dense, it is usually “cold” and doesn't cause significant charging. The equatorial ionosphere and the plasmasphere are such regions. If the plasma is very dilute (density $< 0.05 \text{ cm}^{-3}$), photoemission dominates, and a satellite with a conductive surface will have a positive potential. This occurs, for example, in the near-Earth tail lobes.

Thus, significant surface charging occurs where the plasma is "hot," such as in the near-Earth plasma sheet and its extension to lower altitudes in the auroral regions. The plasma-sheet electrons have average energies of a few hundred to several keV and densities of ~ 0.1 to $\sim 1 \text{ cm}^{-3}$. During substorms, a hot plasma is injected from the magnetotail into the nightside high-altitude equatorial regions, as indicated in Figure 2. The gradient-curvature drifts of the particles in the magnetosphere's magnetic and electric field cause the keV electrons to drift towards dawn. These freshly injected electrons cause dramatic changes in the satellite charging levels. The motion of the electrons drift leads one to predict that the greatest negative charging levels will be observed beyond the plasma-sphere in the midnight through dawn region of the magnetosphere.

The auroral extension of the plasma sheet, from a few hundred km upwards, has a mixed plasma, combining low-density, high-temperature electrons from the equator with cool ionospheric electrons with higher densities. During substorms, electric potential drops occur along auroral magnetic-field lines in order to provide the upward currents demanded by the coupled magnetosphere-ionosphere system. Density "cavities" can appear at ionospheric altitudes, and the average electron energies rise because hot electrons are accelerated downward to lower altitudes to provide the current. This combination of lower background density and raised electron energies causes satellites to charge in the low-altitude auroral regions,² especially in the shadowed and wake regions of the satellites. When the background density is lowered, during auroral activity, the whole satellite can charge if it is in Earth shadow; otherwise, the self-shadowed portions will charge.

2.1.2 Equatorial Satellite Surface Charging

As Figure 2 showed, the plasma sheet electrons in the inner magnetosphere have a preferred drift from near midnight to dawn local time. Very early statistical studies of satellite anomalies showed spatial distributions reminiscent of these electron drift patterns. An example of these anomaly patterns is shown in Figure 3.³ All these anomalies were on geosynchronous satellites, with each plotted at the local time it occurred. (The radial position is arbitrary.) Most anomalies occurred in the 2300 to 0600 local time region. Comparisons of plots like those in Figures 2 and 3 convinced people that the anomalies were probably caused by satellite charging. These plots, combined with the plasma observations, showed that the ATS 5 satellite structure had charged to several kilovolts.^{4,5,6} This convinced the scientific and engineering communities that satellite charging was a problem that

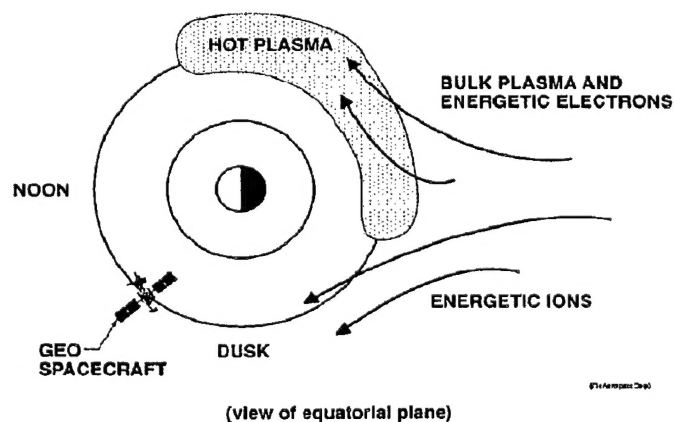


Figure 2. Substorm plasma injection.

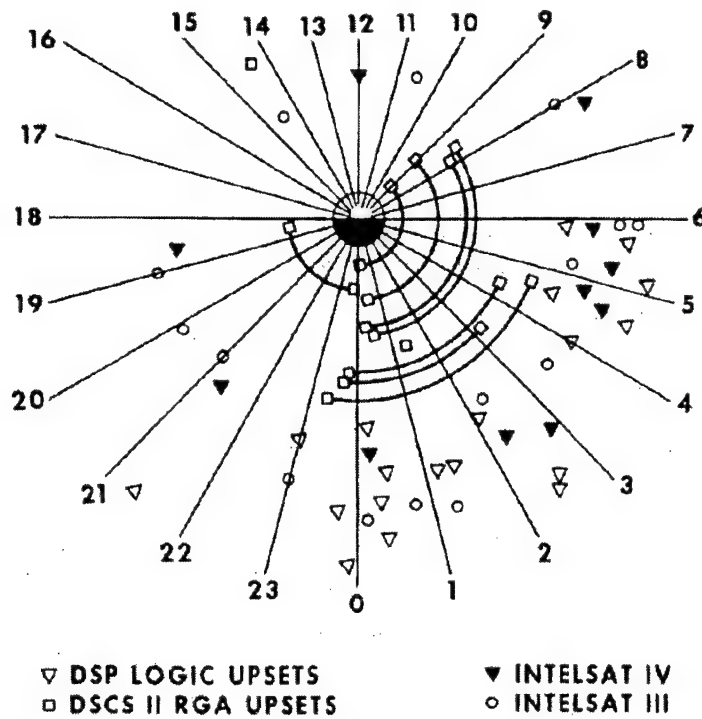


Figure 3. Local time dependence of anomalies observed on geosynchronous satellites.

needed to be understood, and that mitigation strategies needed to be found. Such equatorial surface charging has been linked to substorm plasma injection specifically and magnetic activity in general.

An example of a substorm injection of hot plasma and the subsequent charging of the SCATHA satellite⁷ is shown in Figures 4 and 5. Figure 4 shows spectrograms of the plasma data from SCATHA.

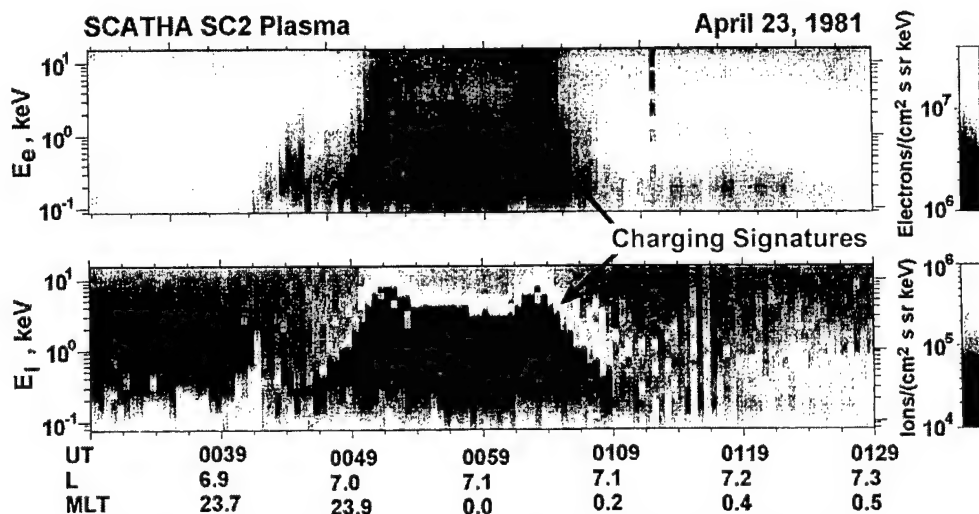


Figure 4. SCATHA plasma spectrogram showing evidence of satellite charging in both electrons (top panel) and ions (bottom panel).

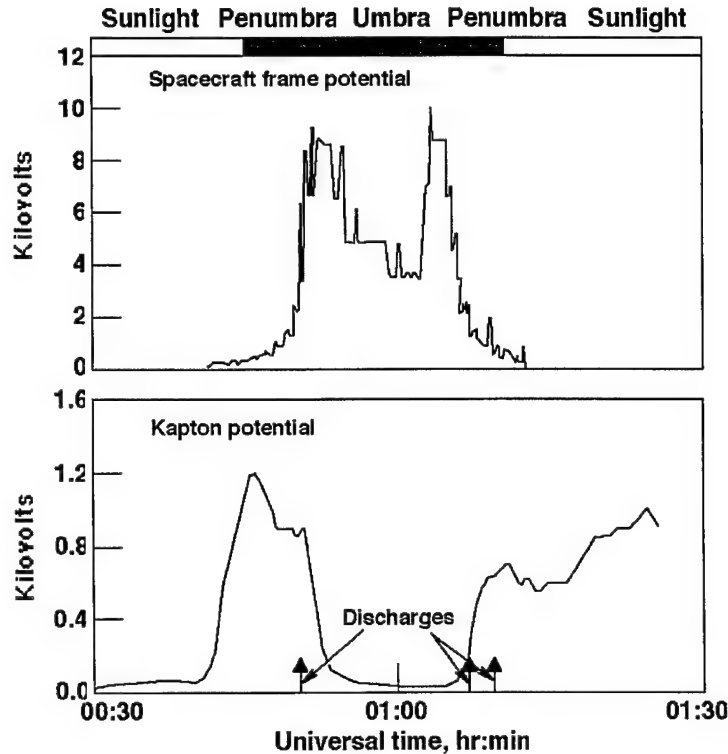


Figure 5. Example of substorm-related charging near midnight. The spacecraft frame potential is shown in the top panel, and the potential of a Kapton thermal blanket is shown in the bottom panel. The potentials were negative.

The substorm plasma injection occurred near 0040 UT. The satellite structure potential (relative to the plasma) is identified by the fact that “cold” ions (bottom panel) are accelerated into the analyzer, creating a bright, low-energy bound the spectrogram. These ion “acceleration” features indicate that the satellite was charged negative relative to the plasma. The plasma electrons (Figure 4 top) also show evidence of negative charging. The electron fluxes are reduced, and the spectrum is shifted by the effective “retarding” potential of the satellite. These data were used to generate a temporal profile of satellite potential relative to the plasma, as shown in Figure 5 (top panel). Figure 5 also shows (bottom panel) the potential of a Kapton thermal blanket sample on SCATHA (measured by an electrostatic voltmeter). The Kapton sample started to charge with the substorm onset, and its potential relative to the satellite frame continued to increase while the frame potential stayed low, initially, relative to the plasma. As the satellite entered the Earth’s shadow near 0046 UT, its frame proceeded to charge to high levels, as shown in both Figures 4 and 5. Upon entering eclipse, the differential potential between the Kapton and the satellite frame decreased rapidly. The sequence was reversed as SCATHA exited the eclipse. Electrostatic discharges were detected during the periods of rapid changes in the potentials associated with the eclipse entry and exit. This example contains many of the common features of surface charging observed by SCATHA. These are: (1) Each dielectric material and the satellite frame responded differently; (2) Discharges tended to occur when the potentials were changing rapidly; and (3) The potentials were never stable during an event, whether it occurred during eclipse or not. Data similar to the Kapton potential data in Figure 5 were used to produce statistical maps of surface charging for the SCATHA orbit. One such map is shown in Figure 6. This map shows that satellite charging in the near-geosynchronous orbit region follows the

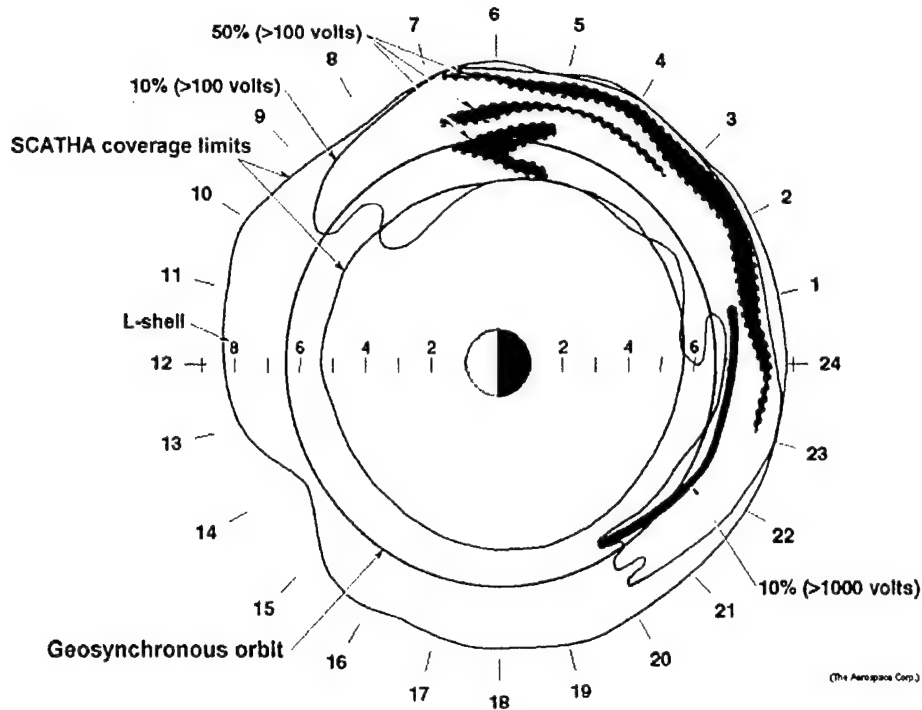


Figure 6. Location of surface charging as determined by SCATHA.

same pattern as that expected for the drift of few to 10's of keV electrons. Figure 6 shows local time features similar to those observed in the geosynchronous satellite anomaly maps like Figure 3.

The relationship between magnetic activity and charging-related anomalies becomes clear when one plots the occurrence of geosynchronous satellite anomalies against a magnetic disturbance index like Kp. Figure 7 shows an example of such a comparison. Statistically, the distribution of all Kp values peaks near Kp = 2 and falls steeply toward smaller and larger values. The steep rise in anomaly

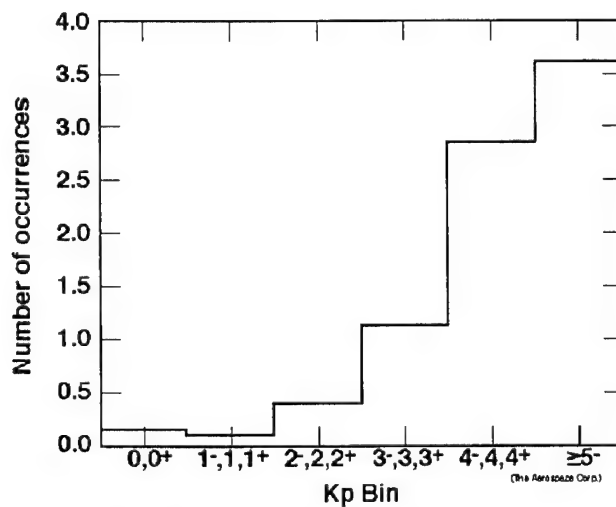


Figure 7. Anomaly occurrence versus Kp.

occurrence with increasing Kp, shown in Figure 7, means that the satellite anomalies are associated with high levels of magnetic activity of the kinds experienced during substorms and magnetic storms. The local time pattern of anomalies and charging, the Kp dependence of the charging (not shown) and satellite anomalies, and the direct observation of satellite charging in response to substorms all link the charging and anomalies to the substorm process. However, we must make it clear that while all surface charging can be tied to substorms, not all substorms will lead to satellite charging.

2.1.3 High-Altitude Off-Equator Satellite Surface Charging

Observers recognized that the auroral displays were associated with disturbances in the high-latitude geomagnetic field. They argued that aurora were caused by currents flowing high above the Earth in the lower ionosphere. The events associated with the rapidly appearing and moving auroral forms and magnetic disturbances were denoted "auroral substorms or magnetic substorms" because of their association with these phenomena and the "stormy" appearance they had, coming and going suddenly and with "violence." Observers also linked the occurrence of massive auroral displays with solar activity such as flares. Over time, it became obvious that the auroral emissions and the currents were the result of enhanced precipitation of energetic electrons, and that the electron precipitation was associated with the substorm plasma injections that were observed at geosynchronous orbit. In the end, the auroral substorm, magnetic substorm, and plasma injections were recognized as different aspects of the same processes called a magnetospheric substorm.

Given these linkages, one might expect that the hot electrons that reached the atmosphere at high latitudes could charge satellites flying through those regions. Under the right conditions, these "hot" auroral electrons can charge low polar-orbiting satellites in a manner similar to what occurs at geosynchronous orbit. This has been borne out by the fact that DMSP satellites have charged to fairly high levels,⁸ and one has experienced an anomaly associated with such charging.² These observations have identified the conditions that give rise to charging at low altitudes (~850 km) in the auroral zones; i.e., if the plasma density is lowered, the average energy of precipitating electrons is raised, and the satellite is in shadow (eclipsed by the Earth) or is self shadowed, then it can charge. The substorm processes, which enhance the precipitating electron fluxes, cause the development of potential drops along the magnetic field lines in order to accelerate the electrons earthward. These potential drops are also regions of ion upflow and lowered background plasma density. For some substorms, the changes in the average electron energy and the plasma density can be extreme. Figures 3 and 4 of Ref. 2 show just such conditions, with the result that the DMSP F13 satellite frame charged to several hundred volts, and a subsystem on the satellite experienced anomalous operation.

The same plasma sheet plasma that maps to the auroral regions exists all along the high-latitude field lines such that any satellite that intercepts these field lines is connected to equatorial charging regions and can experience surface charging. This was first borne out by the occurrence of anomalies on HEO/Molniya orbit satellites. Their orbits have high apogees and latitudes (~40,000 km and 63°, respectively). They cross magnetic field lines that map to the equator from well inside geosynchronous orbit to significant distances from the Earth, corresponding to the equatorial crossing points poleward of auroral field lines. One can use a magnetic field model to project the position of such satellites along the field lines to the magnetic equator. If one does this for each anomaly observed, then one obtains a local time and distance pattern for the anomalies like that shown in Figure 8. It is immediately obvious that the spatial distribution of these high-altitude, high-latitude anomalies mir-

rors the pattern expected for substorm-injected electrons and satellite charging near the magnetic equator. This pattern convinced us that the satellites in question were suffering surface charging-related anomalies.

The authors later flew a simple plasma analyzer on a satellite (designated HEO 95-034) in this same orbit. Figure 9 shows an example of charging that was observed as the satellite few poleward and to higher altitude. When the plasma instrument was turned on at $L \sim 5.4$ the satellite was already

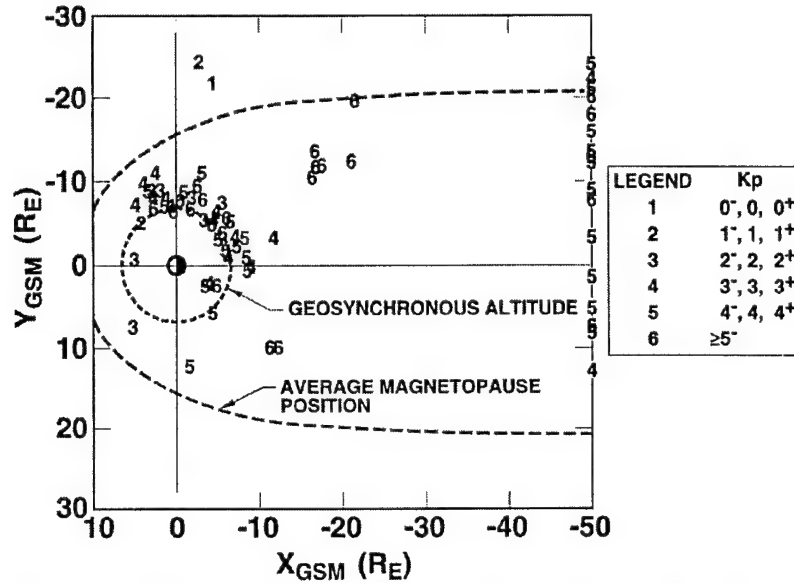


Figure 8. HEO anomalies mapped to magnetic equator. Symbols indicate Kp value.

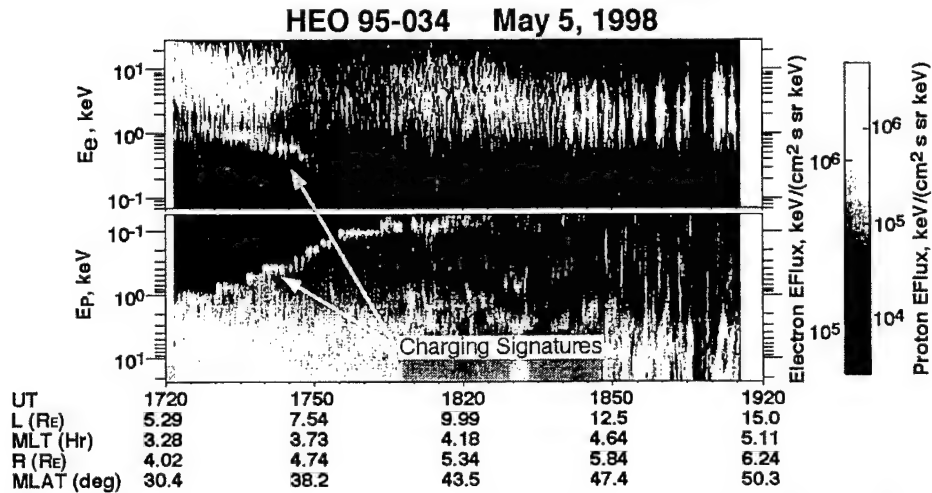


Figure 9. Plasma electrons (top) and ions (bottom) from the Aerospace HEO 95-034. The data show charging signatures during 1720–1820 UT. The satellite was on field lines that map to regions extending below and above geosynchronous altitudes.

charged. The charging level slowly decreased as the satellite went to high magnetic latitude and larger L . Charging signatures are visible in both the electron and ion data. This indicates that there were two parts of the satellite at different potentials. The satellite structure potential is negative as the ion acceleration features indicate. (The plasma instrument is grounded to the satellite structure.) Similarly, the bright low-energy bound in the electron spectrogram is caused by photo emission or secondary-electron emission by a surface that is charged negatively relative to the satellite structure. The electrons emitted from the charged surface leave with a minimum energy equal to the surface potential relative to the plasma. They are detected by the plasma analyzer at an energy that is equal to the difference between the potential of the emitting surface and the structure ground. The magnitude of the potential of the electron-emitting surface relative to plasma would be the sum of the two potential estimates. For this case, it was as much as 1.7 kV

Examination of many orbits of HEO 95-034 plasma data provides a map of the regions where off-equatorial satellite charging occurs. Figure 10 is one such map for intervals when the satellite frame was charged to more than 100 V. The squares [■] and dots [●] correspond to the lower and upper bounds in L , respectively, of the charging region during a satellite traversal. The local time pattern of the charging is consistent with the SCATHA charging pattern (Figure 6), except it extends to higher L . The lower L bound of the charging starts just outside the plasmasphere and extends somewhat lower than the region covered by SCATHA. The range of L in which charging occurred extends into the auroral zone, including both discrete and diffuse auroral regions. This would be consistent with our present understanding of the spatial regions accessible to the few to 10's of keV electrons that are injected into the nightside inner magnetosphere during magnetospheric substorms.

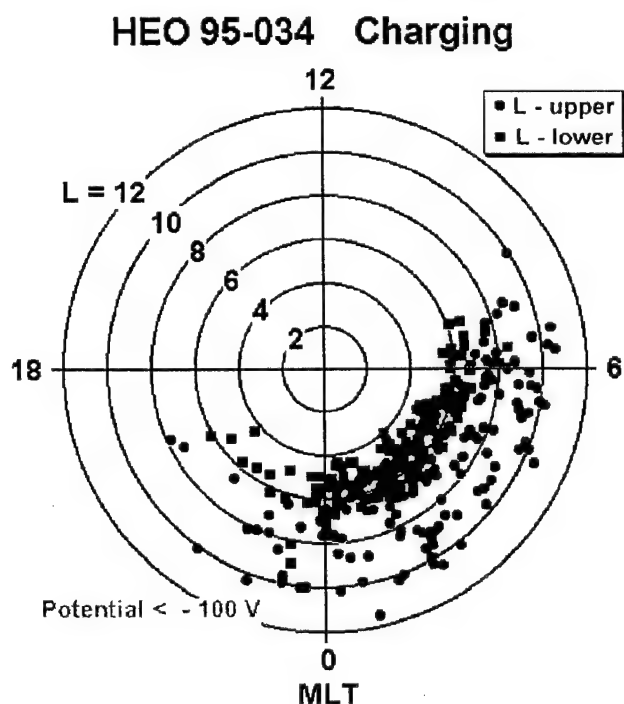


Figure 10. Occurrence of >100 V satellite frame potentials in HEO/Molniya orbit. The symbols mark the upper and lower bounds in L for each charging interval.

2.1.4 Complexities of Surface Charging

Figures 4 and 5 show the apparent simplicity of the surface charging process and its inherent complexity. The correlation of the satellite frame charging with the increased mean energy of the electrons caused by the substorm injection is, at first look, quite simple. However, Figure 5 shows that tracking the satellite frame potential is not the whole answer. The potential of the materials on the satellite do not track the frame potential but respond in their own way. The differential potentials that develop between the satellite's surface materials and the grounded structure are complex, in fact, more complex than even these figures indicate.^{9,10,11} The hazards caused by spacecraft charging result from complex interactions between the space environment and the materials and ESD and electronics on a spacecraft.

There is some evidence that the shape of the distribution function is important to surface charging. At low energies, the secondary-electron yield from surfaces is high. Thus, if the low-energy flux is large, it may prevent spacecraft from charging compared to environments with identical high-energy fluxes but small low-energy fluxes. This makes it difficult to predict charging periods and to understand whether satellites with mixed surface materials will charge and to what degree. More importantly, will ESD occur, and will the satellite's electronics respond? Figure 11 provides a good example of what the space weather community is up against in trying to predict satellite charging. It shows, as the solid line, the electron spectrum that was observed during a sunlight charging event that produced the most and largest discharges on SCATHA for any single day.¹² An "average" electron spectrum, taken at the same spatial coordinates on 15 different non-charging days, is shown for comparison. The days were chosen to be representative of normal conditions. The vertical bars indicate the range of flux variability during the 15 days. One sees that the extreme charging environment differs little from the maximum in normal daily variations. It is only slightly higher in the 10–100 keV range. Yet, the response of SCATHA to this difference was quite extraordinary.

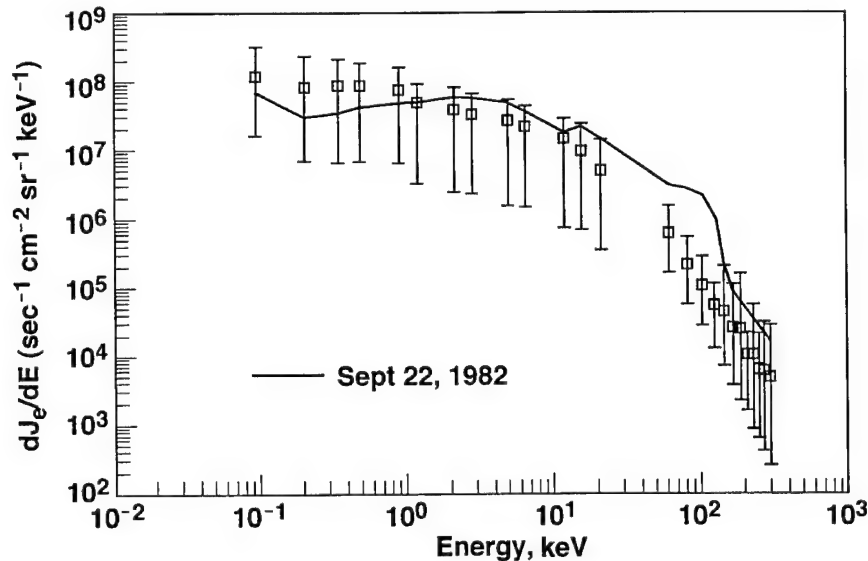


Figure 11. Comparison of a "Worst-Case" plasma electron spectrum and an average electron spectrum. Note the similarities.

Finally, we show one other observation that ties the concept of substorm electron injections with surface charging and satellite anomalies. Figure 12 shows the local time distribution of ESD during surface charging events on SCATHA. All spurious signals from SCATHA operations, such as the ion and electron emitters, the transmitter and command receiver ON/OFF changes, etc., were eliminated from the dataset. Only the remaining noise pulses that occurred during periods that the satellite exhibited surface charging were plotted. The local time pattern is much like that in Figures 2, 3, 6, 8, and 10. These then link the observations of surface charging with predictions of how injected electrons drift with observations of ESD noise and with satellite anomalies.

2.2 Internal Charging

What is internal charging? It is simply the deposition of charge on the internal elements of a satellite by electrons with sufficient energy to penetrate through the satellite skin. In some cases, the electrons deposit their charge in thick dielectrics near the surface of the satellite, in the interior, or on isolated conducting structures inside the satellite. In any case, if the leakage path to ground is sufficiently resistive, the charge can build up over time until arcing or ESD occurs. If the charge is on a conductive element, all the charge is removed from the element by the discharge and deposited in surrounding, usually grounded, elements. If the charge resides in a dielectric, the dielectric may "break down" from high-voltage stress, and some (but not all) of the charge will flow away. The energy in the discharge can be coupled into electronics as a fast signal or can over-voltage devices and damage them. Internal charging can lead to satellite anomalies by this mechanism. Most of the time, the satellites can recover from the anomaly. In rare cases, the anomaly can cause vehicle operations to be suspended or can even be fatal.

As is shown in Table 1, internal charging causes a significant fraction of charging-related anomalies. Once surface charging was established as a serious and real threat to satellites, the question of whether the space radiation was sufficiently intense that it could actually charge items in the interior of satellites was raised. Initially, the high-energy component of the space environment was examined

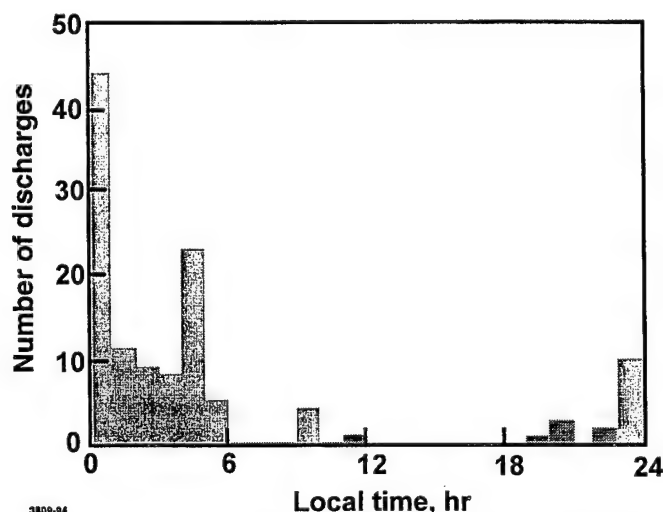


Figure 12. Local time distribution of surface ESD on SCATHA.

to assess how the radiation dose it gave to surface materials might affect the performance of the materials from the surface charging perspective. Later, it was realized that in the heart of the inner magnetosphere, the energetic electron fluxes with sufficient energy to penetrate significant thickness of satellite materials could cause internal charging. This led to the examination of the possibilities for internal charging (or bulk charging as it is sometimes called) of satellites.

2.2.1 Internal Charging Observations

Some of the first data that hinted that internal charging might be a cause of satellite problems came from the SCATHA satellite.¹³ Figure 13 shows the local time distribution of ESD pulses that were detected on SCATHA and determined to be from internal discharges. These were identified as internal discharges by a process of elimination. The noise pulses detected were not associated with commanding of the satellite or with any instrument operations known to cause a response in the ESD detectors. In addition, neither the satellite nor any of the surface materials that were monitored were charged at the time that these noise pulses were detected. This caused Koons¹³ to interpret the pulses as due to internal ESD. Note that these internal discharges have a slight peaking near local noon. This may result from the fact that a near-geosynchronous satellite is on lower L values near noon than near midnight because of the asymmetric magnetospheric magnetic field. The penetrating electron fluxes tend to peak inside geosynchronous orbit, and, thus, would more rapidly charge the interior of the satellite when it was near noon.

Once one accepts the existence of internal charging that can lead to ESD, a reexamination of Figures 3 and 8 leads one to suspect that some of the anomalies plotted there may have been caused by internal charging. For example, in Figure 3 there are a few anomalies in the noon sector. Similarly, there are a few anomalies that occurred on the HEO/Molniya satellites (Figure 8) in the noon sector. So far, there have not been any observations of high levels of surface charging in the noon sector. This is consistent with the fact that the plasma electrons are much reduced in flux by the time they drift to noon. It is most likely that there were internal charging effects on satellites from the beginning, but they were not recognized as such initially.

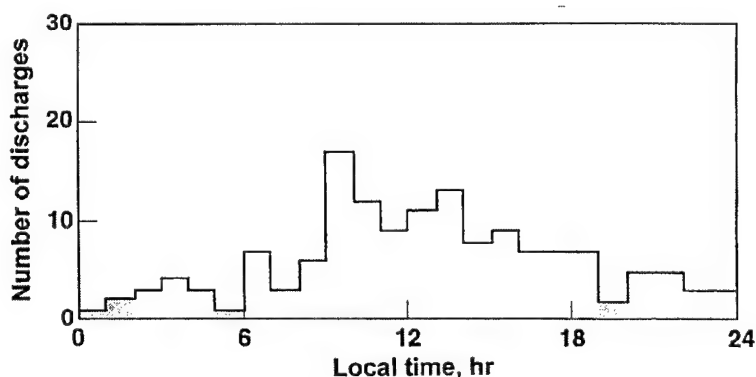


Figure 13. Local time distribution of internal ESD on SCATHA.

2.2.2 Causes of Internal Charging—Magnetic Storms

A common source of the interplanetary conditions that lead to energetic electron enhancements in the inner magnetosphere are magnetic storms. Magnetic storms are often generated by coronal mass ejections (CMEs). The earthward-directed CMEs often appear as “magnetic clouds” with high bulk speed and a structured magnetic field. The interplanetary magnetic field of a magnetic cloud “rotates” in a direction relative to the Earth-Sun line, often presenting a strong southward magnetic component. These changes in the field direction can take hours, which means that the interplanetary magnetic field impinging on the Earth’s magnetic field can be southward for hours simultaneous with a high-speed solar wind and sometimes elevated solar wind density. This combination causes an efficient coupling of the solar-wind energy into the magnetosphere. The energy is coupled into the plasma in the magnetosphere and enhances the electric field (and convection) and diffusion processes there. This may result in a large enhancement in the ion fluxes drifting into and through the magnetosphere from the nightside. These ions carry enhanced energy and current. The magnetic field from the drifting ion current opposes the Earth’s magnetic field, leading to a reduction of the field at the Earth’s surface. This current is called a disturbance ring current and is characterized by a magnetic disturbance index D_{ST} . The geoeffective “size” of a CME or magnetic cloud-associated magnetic storm can, in some sense, be quantified by the magnitude of D_{ST} . As the D_{ST} rapidly drops (the main phase of the storm), the energetic electron fluxes are often reduced significantly in the inner magnetosphere.¹⁴ As the D_{ST} starts to recover, the energetic electron fluxes also recover (at least partly). If the interplanetary conditions are just right, the energetic electron fluxes will increase by orders of magnitude over their pre-storm values. It is these post-storm enhancements in the energetic electrons that can often cause internal charging problems for satellites.

2.2.3 Causes of Internal Charging—Energetic Electron Variability

The energetic electron fluxes ($E_e \geq 300$ keV) in the inner magnetosphere are known to be highly variable, and their variability is tied to the variability of the solar wind velocity.¹⁵ (Paulikas and Blake, 1979). More recently, it has been shown that the enhancements in the energetic electrons requires not only an enhanced solar wind velocity but also a southward component of the interplanetary magnetic field at the same time.¹⁴ Even more recently, there is evidence that the energetic electron-flux levels may be related to the fluctuations in the solar wind velocity (see Ref. 16 and references therein). They argue that these variations drive the diffusive transport of electrons into the inner magnetosphere, causing large variations (orders of magnitude) in the electron fluxes. Figure 14 shows an example of the energetic electron-flux variability at geosynchronous orbit. During the interval shown, there was a nearly periodic arrival of high-speed solar wind streams at Earth. The energetic electron fluxes varied by orders of magnitude. In particular, they exceeded the predicted average levels by more than an order of magnitude for days at a time. Some satellites experienced anomalies during this period that were ascribed to internal charging.

2.2.4 Relation between Internal Charging ESD and Penetrating Electron Fluxes

Both SCATHA⁷ and CRRES¹⁷ carried science and engineering instrumentation that could measure ESD from charging, as well as the electron fluxes that could cause it. Figure 15 shows one example of the kind of data obtained. It shows the increased frequency of internal discharges detected by SCATHA with increasing average energetic electron flux. SCATHA and CRRES both showed that

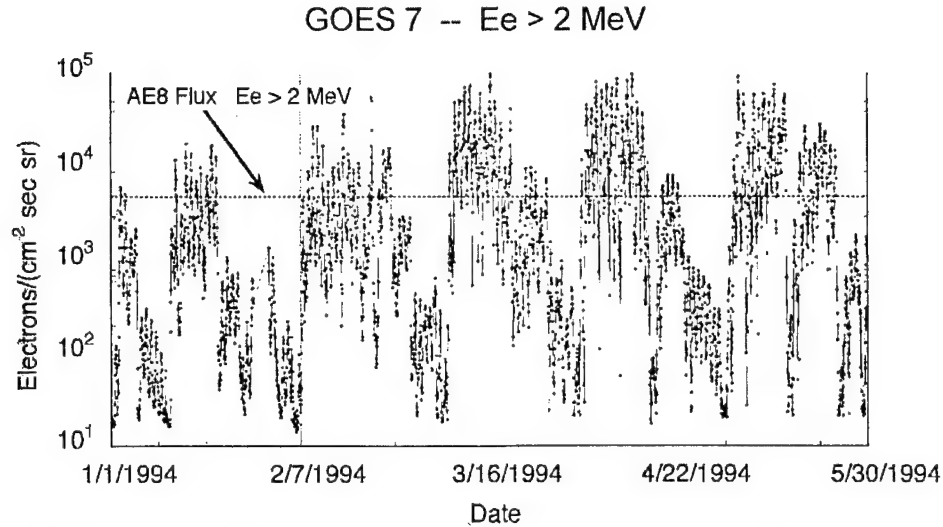


Figure 14. Variation in the energetic electron fluxes at geosynchronous orbit during a period of successive high-speed solar wind streams in 1994.

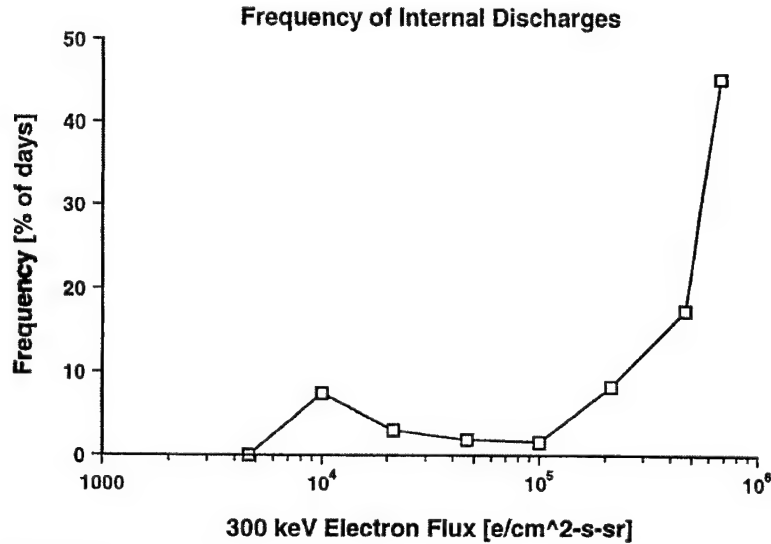


Figure 15. Comparison of SCATHA anomalies with energetic electron fluxes.

when average fluxes of 300 keV electrons were greater than 10^5 electrons/(cm² s sr), the rate of internal discharges increased dramatically. Frederickson et al.¹⁸ indicated that a ten-hour-average penetrating-electron flux greater than 10^5 /(cm² s) was a possible reference level for the onset of discharges from internal charging. This level has been adopted by others (Ref. 19 and references therein) as the maximum average flux that should be allowed to penetrate into the interior of a

Whether discharges from internal charging occur or not depends on the amount of shielding a satellite has to protect its sensitive circuitry. Figure 16 shows how added shielding reduces the level of electron fluxes that can reach the satellite's interior. The peak levels of electron fluxes depend on the effectiveness of the magnetic storm for enhancing the fluxes. The maximum average electron fluxes experienced by a satellite depends on its orbit. A satellite that spends a long time in the heart of the

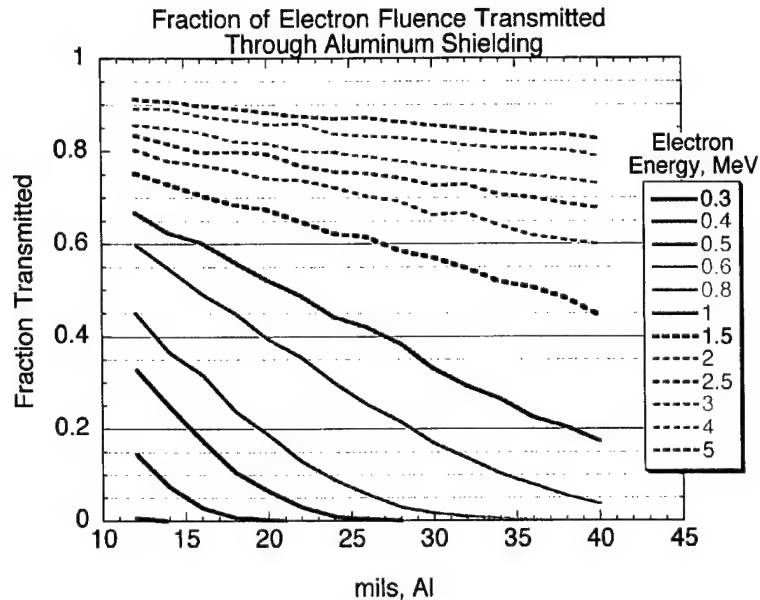


Figure 16. Fractional reduction in electron flux by aluminum shielding.

radiation belts, as the GPS satellites do, will experience very high fluxes and require very thick shielding to protect them from internal charging.

2.2.5 Internal Charging Specifications

The major unknown in the problem of internal charging is what the worst electron fluxes may be. For example, what is the result of a “100-year” magnetic storm? Since we have only been making space plasma measurements for slightly more than 30 years, it is possible we haven’t even experienced the “worst-case” storm. It is only in the last decade or so that we have had continuous monitoring of the energetic particle fluxes in the inner magnetosphere and then only for $L \geq 4$ at the magnetic equator. However, SAMPEX and Polar comparisons have shown that a low-altitude polar orbiting satellite can usefully monitor the variability of electron fluxes over a range of L s.²⁰ To date, the energetic particle measurements needed to specify the extreme conditions have not been routinely taken throughout the inner magnetosphere where internal charging is a problem.

One can examine the electron environment for a few orbits where sufficient data exist. One can intercompare measurements taken by different satellites to try to infer what the worst-case fluxes could be. Fennell, et al.¹⁹ (2000) have done this in a preliminary way using CRRES, HEO, GPS, and geosynchronous energetic electron data. The storm time data from these spacecraft were examined, and it was found that the great magnetic storm of March 1991 was a good representation of the worst-case storm (to date) for a range of L from geosynchronous Earthward. Fennell, et al.^{19,21} used those data to generate worst-case average spectra for a few special satellite orbits. They selected a 10-h interval as the averaging interval based on the work of Frederickson, et al. Examples of the resultant 10-h average spectra for geosynchronous (GEO), HEO/Molniya (HEO), and a lunar transfer phasing trajectory (MAP) orbits are shown in Figure 17. The kind of shielding required to protect satellites in HEO and geosynchronous orbit from suffering internal charging problems can be derived from these spectra. The results of such a calculation are shown in Figure 18 for HEO and GEO. The line at 10^5

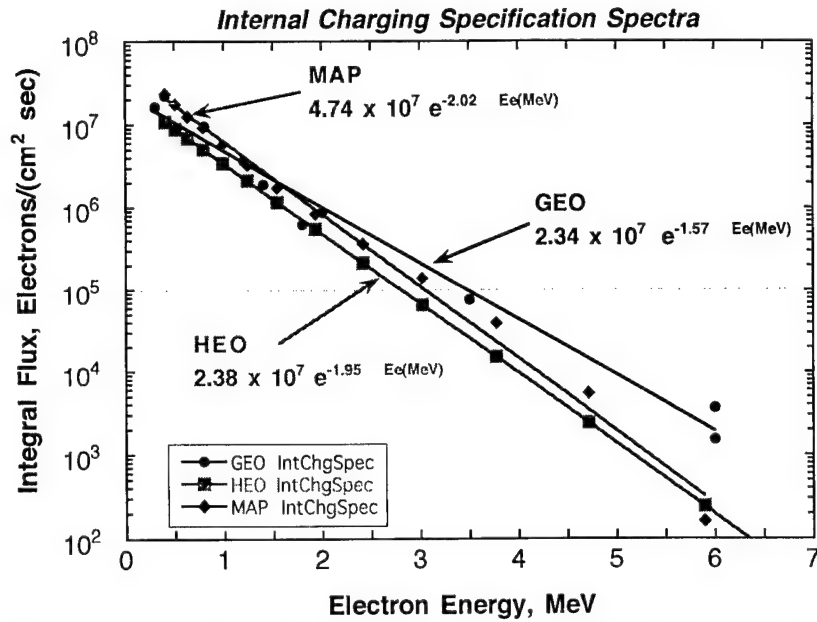


Figure 17. Examples of worst-case 10-hour-average electron spectra for three different orbits.

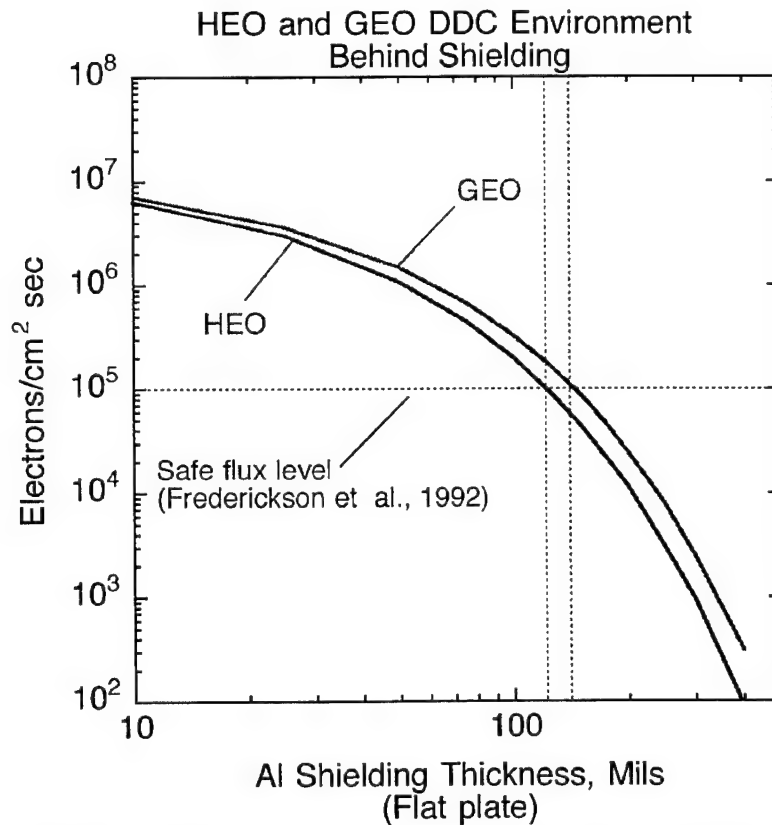


Figure 18. Shielding required to protect HEO and GEO satellites from the worst-case average electron spectra.

electrons /($\text{cm}^2 \text{ s}$) is a reference level at which internal discharges may occur. Whether they do or not and whether they cause severe problems for satellites in those orbits or not depends on much more than the electron fluxes. The technology and engineering design practices used during spacecraft development also play a role, but that is outside the scope of this report.

Figure 18 represents the kind of shielding levels that are required to withstand the “worst-case” fluxes that can be generated by a magnetic storm. However, it must be realized that these are the worst fluxes that have been observed (within a factor of two or so) to date and could be exceeded by the next large storm. We are still taking data and are examining the results from past measurements using “extreme event” statistics to try to determine the probability that these are close to being the equivalent of “30-year” storm levels.

3. Discussion

The linkage of substorms with surface charging and magnetic storms with internal charging is clear, as noted above. Where the difficulty lies is in (1) predicting when storms and substorms will occur, (2) predicting the particle environment that will result, and (3) predicting whether the environment will cause a problem for a given satellite. Let us look at these three difficulties for the surface and internal charging separately.

Predicting substorms seems to be impossible at the present stage of our knowledge. While there is a general description of what occurs once substorm onset has happened, there is not a capability to predict substorm onset. We have clues that a substorm may occur, such as the increase in magnetic flux in the magnetotail lobes and the stretching of the tail exhibited by the change in field character from dipolar to non-dipolar in the near-geosynchronous regions. There are corresponding changes in the particle distributions as the particles attempt to maintain their adiabatic motions. However, many times, the system relaxes back to its unstressed state without a substorm. When substorms do occur, we cannot predict the onset time with any accuracy. We also cannot predict the changes in the particle distributions that, in turn, cause the surface charging. For example, we cannot predict the spectral shape of the electrons nor the exact spatial regions that will experience the enhanced hot-electron fluxes that cause charging. Finally, we cannot predict whether a specific satellite will suffer problems from a given substorm environment. There are too many imponderables. Two "identical" satellites often respond to the same environment in different ways because they are never identical from the environment interaction perspective.

The capability to predict magnetic storms is much greater than for predicting substorms. However, we are far from making reliable predictions. The recent work with SOHO has taken us a long way in predicting whether a CME will strike the Earth's magnetosphere. Future advances in tracking CMEs will raise our success rate for predicting the arrival of their effects at Earth to reasonable levels. However, we still do not know whether these events will be geoeffective or to what degree. Work on predicting the field geometry of the "cloud" as it arrives at Earth is progressing. Yet, we have a long way to go before we can hope to predict whether a CME will have a small, moderate, or large effect at Earth. At present, all Earthward-directed halo-CMEs are expected to have large effects, if we believe the news releases. That is obviously not true. Since magnetic storms also have many associated substorms, they are, in some sense, also a source of surface charging events. Even if we ignore the storm-related substorms and focus only on the possible storm enhancements of the energetic electrons that cause internal charging, we are still left with difficulties.

At our present state of knowledge, we could just track D_{ST} and attempt to use it as proxy for enhancements of the energetic electrons. The L position of the post-storm peak in the energetic electron fluxes appears to track D_{ST} fairly well with a delay of a day or more from the time D_{ST} has reached its minimum value.²² What we cannot predict is the spectral shape as a function of L , and that is required for elliptical orbit satellites. For geosynchronous satellites, one could use near-real-time measurements to track the spectra and make near-continuous predictions of the flux behind dif-

ferent shielding thicknesses. Then individual satellite operators could track the levels that they feel are important to them based on their best knowledge of how their system responds to the environment. However, at this point, such near-real-time data is not readily available, and the shielding effects are not estimated continuously.

Therefore, it is clear that we are making steady progress in understanding the relationship between magnetospheric processes and charging-related effects on satellites. We are also making progress toward predicting the occurrence of storms and being able to predict and now-cast whether the storm-related environment changes are approaching problem-causing levels. We still have a long way to go in providing useful predictions to the satellite operators at the high level of confidence they require. This is especially true for surface charging where we cannot predict substorm onsets and resultant environmental changes with any degree of accuracy. The substorm-related surface charging problems are a big challenge for the whole space weather community and are likely to remain so for the near future.

References

1. Koons, H. C., J. E. Mazur, R. S. Selesnick, J. B. Blake, J. F. Fennell, J. L. Roeder, and P. C. Anderson, "The impact of the space environment on space systems," in Proceedings of the 6th Spacecraft Charging Technology Conference, Air Force Research Laboratory, in press, 2000.
2. Anderson, P. C., and H. C. Koons, "Spacecraft charging anomaly on a low-altitude satellite in an aurora," *J. Spacecraft Rockets*, **33**, 734, 1996.
3. McPherson, D. A., and W. R. Schober, "Spacecraft charging at high altitudes: the SCATHA satellite program," in *Spacecraft Charging by Magnetospheric Plasmas*, A. Rosen Ed., Progress in Astronautics and Aeronautics, **47**, p15, 1975.
4. DeForest, S. E., "Spacecraft charging at synchronous orbit," *J. Geophys. Res.*, **77**, 651, 1972.
5. Rosen, A., Ed., "Spacecraft Charging by Magnetospheric Plasmas," *Progress in Astronautics and Aeronautics*, MIT press, 1975.
6. Garrett, H. B., and A. G. Rubin, "Spacecraft charging at geosynchronous orbit-Solution for eclipse passage," AFGL-TR-78-0122, Air Force Geophysics Laboratory, Hanscom AFB, MA, May 1978.
7. Fennell, J. F., "Description of P78-2 (SCATHA) Satellite and Experiments," in *The IMS Source Book*, C. T. Russell and D. J. Southwood, editors, American Geophysical Union, Washington, D. C., 1982.
8. Gussenhoven, M. S., D. A. Hardy, F. Rich, W. J. Burke, and H. -C. Yeh, "High level charging in the low-altitude polar auroral environment," *J. Geophys. Res.*, **90**, 11000, 1985.
9. Mizera, P. F., H. C. Koons, E. R. Schnauss, D. R. Croley, H. K. Kan, M. S. Leung, N. J. Stevens, F. Berkopec, J. Staskus, W. L. Lehn, and J. E. Nanewicz, "First results of material charging in the space environment," *Appl. Phys. Lett.*, **37**, 276, 1980.
10. Leung, M. S., P. F. Mizera, and R. M. Broussard, "Space effects on physical properties of materials," The Aerospace Corp., ATR-82(8378)-1, Nov. 1982.
11. Fennell, J. F., P. F. Mizera and M. S. Leung, "Laboratory and Space Measurements of Materials," Proceedings of the Air Force Geophysics Laboratory Workshop on Natural Charging of Large Space Structures in Near Earth Polar Orbits: 14-15 September 1982, AFGL-TR-83-0046, January 1983.
12. Koons, H. C., P. F. Mizera, J. L. Roeder, and J. F. Fennell, "Severe Spacecraft-Charging Event on SCATHA in September 1982," *J. Spacecraft and Rockets*, **25**, 239, 1988.

13. Koons, H. C., "Summary of environmentally induced electrical discharges on the P78-2 (SCATHA) satellite," *J. Spacecraft Rockets*, **20**, 425, Sept. 1983.
14. Blake, J. B., D. N. Baker, N. Turner, K. W. Ogilvie, and R. P. Lepping, "Correlation of changes in the outer-zone relativistic-electron population with upstream solar wind and magnetic field measurements," *Geophys. Res. Lett.*, **24**, 927, 1997.
15. Paulikas, G. A. and J. B. Blake, "Effect of the Solar Wind on Magnetospheric Dynamics," *Quantitative Modeling of Magnetospheric Processes*, ed. W. P. Olsen, American Geophysical Union, Washington, D. C., 180, 1979.
16. Li, X, and M. Temerin, "Review of the electron radiation belt," *Sp. Sci. Rev.*, in press, 2000.
17. Johnson, M. H., and J. Kierein, "Combined release and radiation effects satellite (CRRES): Spacecraft and mission," *J. Spacecraft Rockets*, **29**, 556, 1992.
18. Frederickson, A. R., et al., "Characteristics of spontaneous electrical discharging of various insulators in space radiation," *IEEE Trans. on Nuclear Science*, **39**, 1773, December 1992.
19. Fennell, J. F., H. C. Koons, M. Chen and J. B. Blake, "Internal charging: A preliminary environmental specification for satellites," *IEEE Trans. on Plasma Science*, in press, 2000.
20. Kanekal, S. G., D. N. Baker, J. B. Blake, B. Klecker, R. A. Mewaldt, and G. M. Mason, "Magnetospheric response to magnetic cloud (coronal mass ejection) events: Relativistic electron observations from SAMPEX and Polar," *J. Geophys. Res.*, **104**, 24885, 1999.
21. Fennell, J. F., and H. C. Koons, "The space environment and spacecraft environmental hazards: An overview," Course prepared for Aerospace Institute and presented to Intelsat Corp, March 2000.
22. Tverskaya, L. V., N. N. Pavlov, J. B. Blake, R. S. Selesnick, and J. F. Fennell, "Predicting the L-position of the storm-injected relativistic electron belt," *Adv. Sp. Res.*, in press, 2000.

LABORATORY OPERATIONS

The Aerospace Corporation functions as an "architect-engineer" for national security programs, specializing in advanced military space systems. The Corporation's Laboratory Operations supports the effective and timely development and operation of national security systems through scientific research and the application of advanced technology. Vital to the success of the Corporation is the technical staff's wide-ranging expertise and its ability to stay abreast of new technological developments and program support issues associated with rapidly evolving space systems. Contributing capabilities are provided by these individual organizations:

Electronics and Photonics Laboratory: Microelectronics, VLSI reliability, failure analysis, solid-state device physics, compound semiconductors, radiation effects, infrared and CCD detector devices, data storage and display technologies; lasers and electro-optics, solid state laser design, micro-optics, optical communications, and fiber optic sensors; atomic frequency standards, applied laser spectroscopy, laser chemistry, atmospheric propagation and beam control, LIDAR/LADAR remote sensing; solar cell and array testing and evaluation, battery electrochemistry, battery testing and evaluation.

Space Materials Laboratory: Evaluation and characterizations of new materials and processing techniques: metals, alloys, ceramics, polymers, thin films, and composites; development of advanced deposition processes; nondestructive evaluation, component failure analysis and reliability; structural mechanics, fracture mechanics, and stress corrosion; analysis and evaluation of materials at cryogenic and elevated temperatures; launch vehicle fluid mechanics, heat transfer and flight dynamics; aerothermodynamics; chemical and electric propulsion; environmental chemistry; combustion processes; space environment effects on materials, hardening and vulnerability assessment; contamination, thermal and structural control; lubrication and surface phenomena.

Space Science Applications Laboratory: Magnetospheric, auroral and cosmic ray physics, wave-particle interactions, magnetospheric plasma waves; atmospheric and ionospheric physics, density and composition of the upper atmosphere, remote sensing using atmospheric radiation; solar physics, infrared astronomy, infrared signature analysis; infrared surveillance, imaging, remote sensing, and hyperspectral imaging; effects of solar activity, magnetic storms and nuclear explosions on the Earth's atmosphere, ionosphere and magnetosphere; effects of electromagnetic and particulate radiations on space systems; space instrumentation, design fabrication and test; environmental chemistry, trace detection; atmospheric chemical reactions, atmospheric optics, light scattering, state-specific chemical reactions and radiative signatures of missile plumes.

Center for Microtechnology: Microelectromechanical systems (MEMS) for space applications; assessment of microtechnology space applications; laser micromachining; laser-surface physical and chemical interactions; micropropulsion; micro- and nanosatellite mission analysis; intelligent microinstruments for monitoring space and launch system environments.

Office of Spectral Applications: Multispectral and hyperspectral sensor development; data analysis and algorithm development; applications of multispectral and hyperspectral imagery to defense, civil space, commercial, and environmental missions.



2350 E. El Segundo Boulevard
El Segundo, California 90245-4691
U.S.A.